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Evaluating Line Relaying Schemes in Terms of Speed, Security and Dependability

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Introduction

There are many different types of relaying schemes that are available today. Each of these schemes offers advantages and disadvantages in terms of speed, security and dependability relative to application to the power system. The various schemes to be discussed are described in detail in Appendix A of this paper.

Speed

General

Critical clearing times for a transmission line are often used to determine the required operating speed for the transmission line protection. These critical clearing times are usually based on close-in three phase faults. It is obvious that a three phase fault at one of the line terminals of the system of Figure 1 would prevent the transfer of any power and thus must be cleared in high speed. For lower source to line impedance rations (Zs/ZL), as the fault is moved towards the center of the line, more power can be transferred during the fault, thus permitting longer operating times. Similarly, a phase to ground fault, even at one of the line terminals, has much less effect on the power transfer capability of the system. In fact, the system may be able to transfer more power during a single line to ground fault than after the breakers have been opened to clear the fault [1,2]. In terms of system stability it is critical to trip the breaker near the fault in high speed for close-in faults to minimize the effect of the fault on the power transfer capability. Once the near end clears, the fault appears as a high impedance fault to the remote terminal and power transfer capability will be increased thus helping to maintain stability. Consequently, it is not so critical to trip as fast at the end of the line remote from the fault.

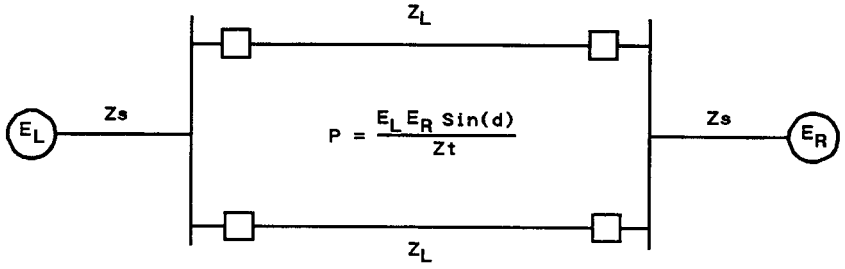

Figure 1 - Typical Power System

Now consider the effects of large source to line ratios (Zs/ZL) which in general imply that a short line is being protected. For this case, it is critical that fast clearing be initiated at each terminal of the

transmission line regardless of the fault location. This is so because the voltage is severely depressed at each terminal of the line and would remain depressed even if one end of the line were to be cleared faster than the other. Power transfer capability and consequently stability can be jeopardized unless both ends of the line are cleared quickly.

Distance Relay Operation

A typical distance relay uses an operating signal that is derived from the reach (Z) of the relay, the current (I) and voltage (V) produced at the relay, IZ – V for example [3]. The magnitude of the operating signal is therefore directly proportional to the current and the reach and inversely proportional to the voltage. The larger the operating signal, the less will be the effect of any transients applied to the relay as a result of a fault. The function can be polarized in a number of different ways. Most functions are provided with memory so that in terms of high speed operation, the relay is using the remembered prefault voltage at the time of the fault occurrence. Operation occurs when the operating signal and the polarizing signal are within a set angle of each other.

Distance/Directional Pilot Relaying

Pilot relaying schemes were developed to provide fast tripping for faults anywhere on the transmission line. Although each of the pilot relaying schemes will provide tripping for all faults internal to the protected line, the speed of operation can vary depending on the scheme and the particular application. Please refer to Appendix A for a more thorough description of each of the schemes.

Blocking Type Schemes

In a blocking type of scheme, each relaying terminal is provided with both tripping and blocking functions. The tripping and blocking functions must coordinate with each other in that the blocking function must operate for all faults external to the line that are within the reach of the remote tripping function. In addition to coordinating on a reach basis, it is just as important that the tripping and blocking functions coordinate on a time basis; i.e., the blocking function should be as fast as or faster than the tripping function. If this coordination cannot be achieved naturally as shown in Figure 2, then additional time delay must be introduced in the scheme logic after the tripping functions operate to prevent tripping for external faults. The amount of time delay that is required must be at least equal to the difference in time between the operation of the tripping function and the remote blocking function. This time delay, once set, will be introduced for all internal faults regardless of the location on the line.

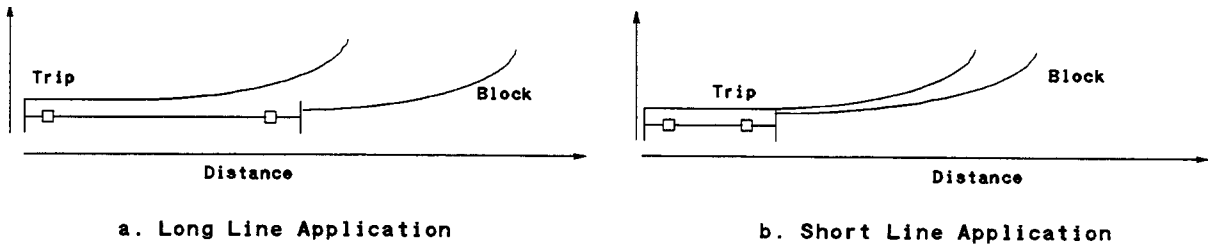

Figure 2 - Long/Short Line Application with Blocking Scheme

The communications channel is used to send a blocking signal to the remote terminal of the transmission line to block the tripping functions from initiating a trip. The speed of the channel (measured from the time the transmitter is keyed to the time the receiver produces an output) is an important consideration in the operation of a blocking type of scheme. This is so because time delay must be introduced after the tripping functions to allow time for a blocking signal to be received before tripping can be initiated. Thus, the faster the channel, the less time delay that will be required and vice versa. Extremely slow channels will result in extremely slow pilot relaying times.

Signal propagation time must also be considered but this time is typically very small for most applications. If the transmission line is used as the medium of propagation, then 1 millisecond of delay will be incurred for each 186 miles of transmission. If a different medium is used, then any additional delays that may be introduced (repeaters, etc.) must be taken into account in setting the time delay.

For the example shown in Figure 2, the trip and block functions coordinate naturally, therefore, no additional coordinating time delay is required, and the trip time for a fault on the line will be equal to the operating time of the trip functions plus the channel time plus the propagation time plus a suitable margin. Typical operating time for a well-designed function will be in the order of 5-6 milliseconds for close-in faults and anywhere from 12 to 25 milliseconds for remote faults (depending on the application). For close-in faults on the long line (Figure 2a), tripping will be very fast (assuming a fast channel) thus meeting system stability requirements. Even faster times can be achieved by the addition of zone 1 direct trip functions which are not affected by channel delay, propagation time, coordination margins, etc. For remote faults, some additional delay will be incurred, but this should not jeopardize system stability because of the length of the line. For the short line application (Figure 2b), the trip functions should be set with sufficient overreach to produce a flat operating time characteristic to provide fast operation at both line terminals for a fault anywhere on the line. Zone 1 direct trip functions may not be beneficial in this situation for the reasons given earlier.

Permissive Tripping Type Schemes

Blocking type functions are not required in permissive tripping type relaying schemes. This makes the schemes much simpler and eliminates the coordination requirements introduced in the blocking type schemes described above. In order for tripping to be initiated in a permissive scheme, a permissive trip signal must be received from the remote terminals of the line. For this reason it is imperative for the trip functions at all terminals of the transmission line to operate as fast as possible. Any delay at any terminal will cause tripping to be delayed at all terminals of the line. Any failure to detect a fault at any terminal will prevent tripping from being initiated at all terminals. Since tripping cannot be initiated until a permissive signal is received via the communications equipment, the channel equipment should be as fast as permissible to minimize any tripping delays.

Permissive tripping type schemes are best suited to applications wherein system conditions are conducive to fast relay operation at all terminals of the transmission line, i.e., strong sources and long reach settings. For example, in the long line application of Figure 3a, a permissive tripping scheme by itself may not be appropriate because of the delay in operating time of one or the other of the trip function for remote line faults. Even though the trip function at the terminal near the fault would

operate fast, overall tripping would be delayed there until the remote trip function operated. The fastest tripping occurs at each terminal for faults near the center of the line rather than for a fault near one of the terminals. For low level fault currents (weak source impedance's), the operating time of the function remote from the fault could be quite long, so that overall tripping could be long enough to jeopardize system stability. If a permissive type tripping scheme is to be used in an application with trip functions that operate as typified in Figure 3a, then zone 1 direct tripping functions should be added to the relaying system to insure fast tripping for close-in faults so that system stability will not be jeopardized. If the tripping functions can be set as shown in Figure 3b, and if the sources are always strong, then a permissive type tripping scheme would be suitable to the application. A fast channel should be used in order to minimize any channel delay.

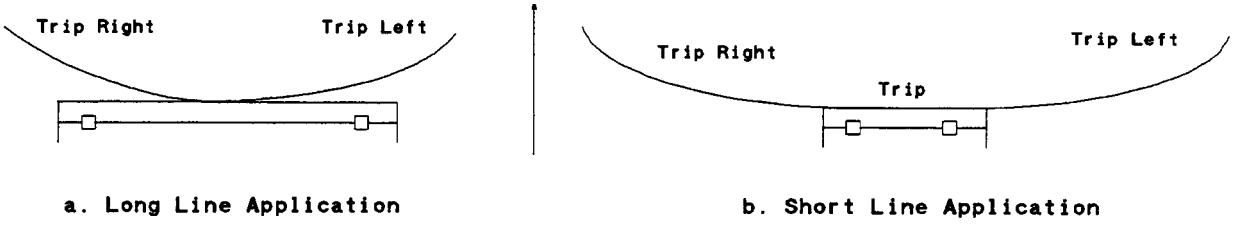

Figure 3 - Long/Short Line Applications with Permissive Tripping Schemes

Hybrid Type Scheme

A hybrid type relaying scheme utilizes tripping and blocking functions as does a blocking scheme but both are used in a slightly different manner. The tripping functions work with the communications channel as in the permissive scheme described above; i.e., a permissive trip signal must be received from the remote terminal in order to initiate tripping. The communications channel can be keyed in one of two ways: by the operation of any one of the tripping functions, or, in the absence of the operation of a tripping function, by the receipt of a permissive trip signal from the remote terminal of the line provided one of the local blocking functions has not operated. The latter method of keying is commonly referred to as "echo" or "repeat" keying, With this feature, any terminal of the line that detects the fault is able to trip even though the other terminals may not have seen the fault (provided none of the blocking functions have operated). For example, consider a fault near the left hand terminal of Figure 2a. The trip functions will operate very fast for this fault and will key their respective transmitter to send a permissive signal to the right hand terminal. The blocking functions at the right will not operate for this fault, therefore the received signal will be "echoed" back to the left terminal to permit tripping there (total trip time at left equals the trip function operate time plus twice the channel plus propagation time). Thus if the right hand terminal was very slow in operation, or perhaps did not operate at all, the left hand terminal would have tripping initiated in a relatively fast time. The terminal at the right could be equipped with the necessary features to permit tripping there (weak-infeed tripping). If faster operating time is required, zone 1 direct trip functions should be added at all terminals of the line.

Zone Acceleration Type Schemes

Fast tripping will be initiated for close-in faults in the zone acceleration schemes, but a trip signal must be sent to the remote terminal to start the measurement there to initiate tripping at the remote terminal. For example, consider the faults at the right hand terminal of the system shown in Figure 4. The trip function at the right will operate for that fault but the trip function at the left cannot because the fault is beyond its non-extended reach. Fast tripping will be initiated at the right and the transmitter there will be keyed to send a trip signal to the left. When the trip signal is received at the left, the reach of the trip function will be extended as shown and once it operates, it will initiate tripping at the left terminal. Thus fast tripping can be achieved at the right, but tripping at the left terminal can be considerably slower (equals trip function time at right plus propagation time plus channel time plus operating time of function at left). If this were a long line application, then the delay may be tolerable from a stability point of view. Such delays may not be acceptable in short line applications.

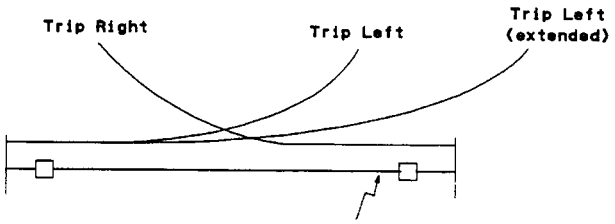

Figure 4 - Zone Acceleration Scheme

Zone 1 Direct Trip Relays

Zone 1 direct trip functions are beneficial in any application because they can provide coverage for 8090 percent of the line independent of the communications channel.

Zone 1 direct trip functions can be made to operate very fast for *close-in faults* in the long line situation (low Zs/ZL) because the operating signal will in general be very large because of the long reaches, high fault currents and low voltages involved. Any transients that may be produced as a result of the fault will in general be very much smaller than the operating signal thus their effect will be minimal. The effects of any filtering that is used in the relay can be minimized by design and the relay can be made to operate very fast for this condition. As the fault is moved further away from the relay, the operating quantity will be reduced in magnitude. Any transients that might be produced as a result of the fault then appear to be larger relative to the operating signal, and some delay in operation would be advantageous to allow time for the transients to subside. The delay in operating time is usually introduced by filtering. Fortunately, this delay only affects the operation of the breaker remote from the faults thus there will be less of an impact on system stability.

For the short line case (high source to line impedance ratios) smaller operating signals can be expected because short reaches have to be used and the fault currents may be lower because larger source impedance's may be involved. Any system transients that are now produced can appear to

be large relative to the operating signal and steps must be taken to insure that improper operation does not occur.

One of the most severe transients that a relay can experience may be introduced by a capacitor voltage transformer (CVT). A typical CVT output is shown in Figure 5 which is typical of the transient output for a very large change in the voltage.

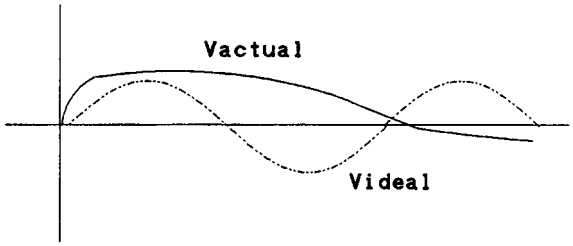

Figure 5 - CVT Transient

Consider the case of a zone 1 direct trip function set to reach 90 percent of the line and applied where the Zs/ZL ratio is high and that a remote bus fault occurs. If a CVT is used to provide the voltage to the relay then the applied voltage can appear as shown in Figure 5. On the other hand, if a potential transformer is used to derive the relay voltage, then the voltage can approach Videal as shown in Figure 5. The effects on the operation of a distance function in each situation is shown in Figures 6 and 7 respectively. For the assumed situation, the zone 1 function should not trip for this remote bus fault. The operating signal and the polarizing signal should be 180 degrees out of phase for this condition. For the ideal case as shown in Figure 6, the 180 degree phase relationship exists. For the case with the CVT transient, this condition does not exist and as shown in Figure 7, the operating signal and polarizing signal are in phase during the second half-cycle which is an operating condition. In other words, the zone 1 direct trip function has overreached. Zone 1 functions can be designed to prevent overreaching in this situation, but high speed operation is difficult, if not impossible to achieve, therefore zone 1 functions can not be relied on to provide fast protection for this situation. If the design is not adequate to prevent overreaching with an 80-90 percent reach, then a pullback in reach will probably be required to provide secure operation. This results in a reduction in the percentage of the line that can be covered by direct trip functions.

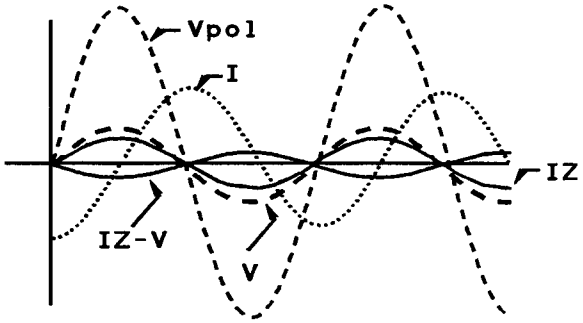

Figure 6

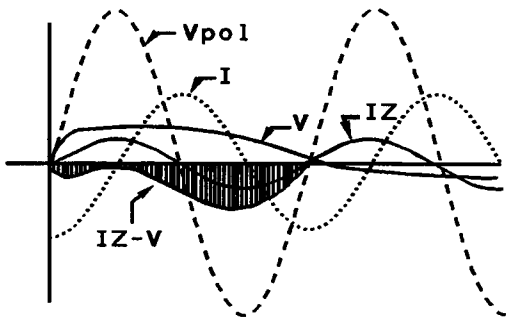

Figure 7

Where low source to line ratios (long lines) or long reaches are involved, the CVT transient is not as onerous and will have little effect on the performance of the function. This is shown in detail in Figure 8. Note that the operating signal is distorted but not to the point that it will affect relay performance. Also note that the operating signal can be quite large thus the function can be made to operate very fast and with security. Zone 1 direct tripping functions are very beneficial in long line applications because they can provide high speed tripping for close-in internal faults where fast tripping is required. They should be used whenever possible.

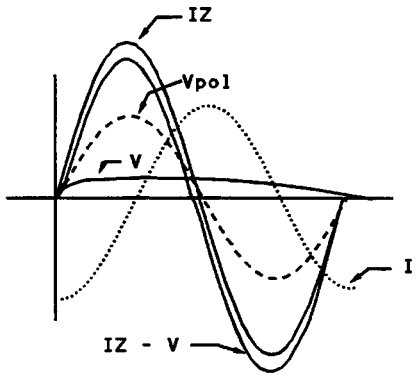

Figure 8

Current Only Pilot Relaying

Phase Comparison Type Schemes

Phase comparison type schemes as pointed out in Appendix A can be of the single-phase comparison type of the dual-phase comparison type. The schemes can be set up to operate in either the blocking mode or tripping mode of operation. In the blocking mode, a channel signal is required from the remote terminal to block tripping for external faults. With this type of scheme tripping will be initiated for all internal faults even if the channel has failed provided the trip detectors operate for the fault. In a tripping type of scheme, trip information is required from the remote terminal in order to initiate tripping. Tripping will not be initiated in the absence of any information. If system conditions can be severe enough to not operate the trip detectors then tripping will be blocked at all terminals of the line. Operating time in phase comparison schemes is dependent on the point in the voltage wave that the fault occurs (determines the instantaneous polarity of the fault current). Overall operating time can be faster for a dual-phase comparison scheme since a comparison is made during both the positive and negative half-cycles of the current signal as opposed to the single-phase comparison scheme wherein a comparison is made only during one of the half-cycles (typically the positive half).

Current Differential Type Schemes

In a current differential type of scheme, a true differential measurement is made, thus information concerning both the phase and magnitude of the current at each terminal must be available at all terminals in order not to operate for external faults. A current differential scheme can however operate

for internal faults even for zero infeed at one or more of the terminals provided the total current is greater than the sensitivity of the system. Fast operation can be expected at the heavy infeed terminals with slightly slower operation at the weaker terminals.

Direct Trip Functions in Current Differential and Phase Comparison Type Schemes

Since current only schemes do not require potential inputs in order to operate, zone 1 type functions can not be employed as part of the scheme, unless the scheme is supplied with provisions for potential inputs. Direct tripping overcurrent functions can be used in these schemes. Since they cannot be made directional (no potential source) they must be set based on the maximum fault current expected for an external fault whether this be directly behind the terminal or at the remote terminal of the line. This setting requirement makes the operation of the functions dependent on both source impedance and line length thus limiting their use (they do not have a defined reach as does a zone 1 distance function).

Reliability: Dependability and Security

The hardware reliability of a relay system can be calculated using defined equations. Unfortunately, there is no easy way to calculate the performance reliability of a relay system. Reliability is a measure of the degree of certainty that a given relay system will perform correctly. In protective relaying, reliability consists of two elements: dependability and security. Dependability is a measure of the ability of a protective relay system to operate correctly when required. Security is a measure of the ability of a protective relay system to not operate incorrectly. An ideal relay system is one that is 100% dependable and 100% secure. While it is impossible to achieve 100% reliability, it is possible to approach this goal with properly designed protective relaying systems.

Dependability

Dependability is considered one of the most important requirements for any protective relay system since the non-operation of the protective relaying equipment can result in the destruction of a power system component and the collapse of the power system. In this discussion, the term "protective relay system" refers to more than a set of relays. The protective relay system consists of the complete complement of protective elements covering a zone of protection (including backup relaying), any associated communications equipment' and power system components such as current and potential transformers.

There are several factors that directly affect dependability. Perhaps the most important factor is the design of the relays and schemes used for protection. The relay measuring elements and schemes should have the characteristics and sensitivity to detect all faults up to the limitations imposed by system and fault conditions. Every relay system has limitations; for example, each relay has a current level (sensitivity) below which it can not respond. Thus, for some low level faults on the line, the protection can not be expected to operate.

Another factor is the availability of the protective equipment. If the equipment is not available to perform its function at the time it is needed, then the dependability of the protective system is reduced. Maintenance and hardware reliability are factors which affect availability. Equipment which requires periodic adjustments, cleaning of contacts, etc. will not be available for protection during the maintenance period, thus reducing dependability. The higher reliability of digital relays, along with their self test features, improve their availability, and therefore the dependability of the protective system.

Security

The security of the relay system is at least as important as it dependability because an incorrect operation of a protective system reduces the overall reliability of the power system. In fact, a review of major system disturbances, such as blackouts, will show that the disturbance is more likely to be caused by the misoperation of a protective system rather than the non-operation of a system. The misoperations may be of the "sympathetic trip" nature, where a protective system on an unfaulted line operates for an external fault; or it may be caused by a miss-set relay that operates due to a short term increase in load caused by the opening of another line in the system. In addition, the security of a protective relay system can be adversely affected by system transients, current and voltage transformer transients, series capacitor transients, surges produced by switching on the high voltage system or in the dc control circuit, and by radio frequency interference. The overall security of a protective system can be greatly improved through the use of relay equipment that are properly designed to perform correctly in the harsh substation environment.

Protective System Considerations

As noted previously, the protective system encompasses more than just the protective relays themselves. The type of protective scheme and the type of communications channel will also affect the dependability and security of the overall protective system.

Blocking Vs Tripping Schemes

The use of a blocking scheme, whether it is distance/directional or current only, tends to improve the dependability of the protection at the expense of reduced security. The dependability is increased because in a blocking scheme only the local tripping units are needed to initiate tripping. For external faults seen by the tripping units, however, any failure to receive the blocking signal from the remote end will result in an over-trip, thus reducing the security. The failure to receive the channel can be the result of a problem with the blocking units at the remote terminal, the channel equipment at either terminal, or a problem in the communications medium between the terminals. Because the typical blocking channel is an On-Off channel without built in monitoring, the addition of a channel checkback scheme tends to increase the availability of the channel by detecting problems. Increasing the availability of the channel also increases the security.

When a permissive scheme is used, the dependability tends to be lower than with the blocking scheme because the tripping units at both terminals must detect the fault and the permissive channel signal must be received. On the other hand, the security tends to be increased because the pro-

tective scheme can not misoperate for an external fault unless a false permissive signal is also received. Since most permissive channels are frequency shift (FSK) channels, they can continuously monitor the state of the guard signal thus increasing the availability of the channel.

The communications medium will have an affect on the availability of the communications channel. The On-Off blocking channel and some FSK channels use the transmission line as the communications medium. When applied in a blocking scheme, the blocking signal is sent for faults external to the line, thus the line is intact and the signal can be expected to get from one end to the other. Conversely, an internal fault will not degrade channel performance since tripping is not dependent upon transmission of a trip signal. Thus, no special features are required in this type of channel for power line carrier applications. When FSK channels are applied on the power line in permissive type schemes, it may not be possible to get the permissive signal from one end to the other because of the fault. In those cases, "UNBLOCKING" type logic should be included in the channel equipment to increase the probability of operation for internal faults. FSK channels may also be applied over microwave, fiber optic, or telephone lines. In these applications it is unnecessary to resort to "UNBLOCKING" type logic because the channel will not be affected by the fault as is the case when the power line is used as the propagation medium.

Multiple Schemes

Dependability can be improved by the quantity and arrangement of the protective equipment. Dual primary relay systems, arranged so that either one will perform the protective function, are often used on many transmission lines. In many instances, the two schemes use different operating principles and use different channel paths. Some utilities will even require that the equipment's be from different manufacturers. The intent is to improve the ability of the overall system to operate through a diversity of measuring elements. When applying dual schemes, the type of scheme that is used should be carefully considered. For example, a blocking type of scheme is very dependable, but is subject to overtripping if the channel is lost. Thus if one scheme is of the blocking type and one scheme is of the tripping type, the blocking scheme introduces a degree of insecurity because of the possibility of overtripping. It would be better to consider two schemes of the tripping or hybrid type which provide security while giving dependability by the use of two schemes; i.e., neither scheme is subject to overtripping for channel failure while either scheme can be expected to operate if the other fails. The blocking scheme would be a better selection if only one primary scheme is used and dependability is more critical than security; i.e. an occasional overtrip might be acceptable.

It is interesting to note that, while the use of dual primary relaying schemes enhances dependability, this practice *reduces* the security. There are now two protective schemes that may misoperate rather than one! In an attempt to avoid this problem, three protective schemes have been used in some critical applications with the requirement that two out of the three schemes operate before a trip is issued.

Current Only Vs Distance Schemes

Current only schemes such as phase comparison or current differential tend to be more sensitive than the distance type schemes. This is because the current only schemes employ simple measuring elements that "see" more faults since they respond only to the magnitude of the current. This tends to make them more dependable but at the cost to security because they will also "see" more external faults. Integrity of the communications channel is very important to the operation of current only schemes and for this reason, the communications channel should be highly reliable and very dependable. Since current only schemes require no potential to operate, they can also be considered somewhat more secure since they are not affected by any problems introduced via the potential inputs. On the other hand, there is no inherent backup included because of the lack of potential inputs.

The distance schemes tend to be more secure than the current only schemes because they have defined reaches and tend to "see" fewer faults external to the zone of protection. These schemes can inherently be used to provide backup protection. Channel integrity is important in these type of schemes but not to the degree required in the current only schemes.

Conclusions

Many different types of relaying schemes are available for the protection engineer to choose from. Each of the available schemes has both advantages and disadvantages in terms of speed, dependability and security. Multiple (dual) relaying schemes are often used in many applications. Each application should be studied individually to determine the system requirements before making the protective relaying scheme selection. Direct tripping functions (zone 1 or overcurrent) should be used whenever possible to provide high speed tripping independent of the communications channel.

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